

Review

A Literature Review of the Digital Thread: Definition, Key Technologies, and Applications

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Abstract: The digital thread, as a crucial technology for industrial digitization and the realization of smart manufacturing, has garnered extensive attention and research in recent years. Furthermore, there is a growing interest in the key technologies supporting the implementation of the digital thread. Given the diversity of product lifecycle models, various definitions, reference architectures, and implementation methods have been proposed to study the digital thread. Thus, this study systematically investigates the current definition, key technologies, and applications of the digital thread. A comprehensive analysis of 94 articles spanning from 2015 to 2023 was conducted, clarifying the definition of the digital thread and its relationship with related terms. Building upon this foundation, this study delves into the research methodologies concerning pivotal technologies in implementing the digital thread (such as authoritative sources of truth, data linkage, and model integration) and scrutinizes various application scenarios of the digital thread, providing a comprehensive summary. Finally, this study presents the research findings along with recommendations for future research endeavors.

Keywords: digital thread; authoritative sources of truth; data linkage; model integration; application



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1. Introduction

The ongoing global industrial revolution has prompted countries to reach a consensus on prioritizing digital transformation and intelligent upgrading for future development. Faced with the increasing complexity of equipment systems, collaboration among enterprises at various stages of the system's lifecycle and along the value chain has become increasingly crucial. The digital thread, as a method linking all systems, processes, virtual data, and physical data, serves to eliminate "data silos" within and beyond manufacturing enterprises. The concept of the digital thread originated during the joint development of the F-35 Lightning II project by the United States Air Force (USAF) and Lockheed Martin. It was introduced to describe the direct input of three-dimensional computer-aided design (CAD) data into computer numerical control (CNC) machining, enabling the finished product to be traced back to the original computer model—a continuous data link referred to as the digital thread [1,2]. In 2013, the USAF first proposed the concept of the "Digital Thread", which was further developed [3]. In 2019, the Department of Defense (DoD) released the Digital Modernization Strategy to guide the information technology transformation of the DoD, providing explanations of concepts such as the digital thread, digital system models, and digital twins, along with clarifications of their inter-relationships [4]. This study examined the developmental trends of the digital thread by conducting a systematic review of papers related to the digital thread published between 2013 and 2023. The search utilized the keywords "Digital Thread", and the databases searched encompassed Scopus, the Web of Science, AIAA, IEEE Xplore, and Google Scholar. The annual distribution of digital thread-related papers is illustrated in Figure 1. From the figure, it is evident that since 2018, the number of papers experienced a sharp annual increase, with over 250 papers in 2022.

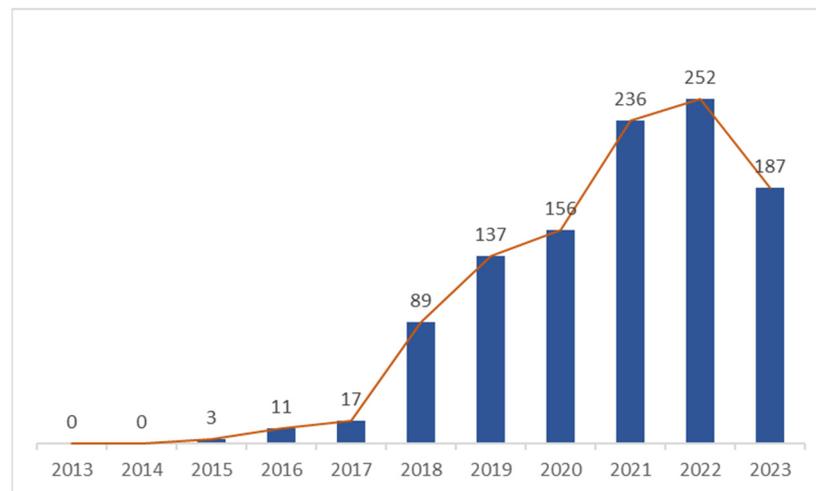


Figure 1. Number of digital thread papers published per year.

The DoD released the Digital Engineering Strategy document in 2018. The concept of digital engineering aims to streamline the DoD procurement process and facilitate all stages of the system lifecycle through the establishment of a digital thread comprising interconnected models alongside logical, mathematical, and simulation representations of the Systems of Interest (SoIs) [5]. The digital thread propagates changes made to the data in one model throughout the entire digital thread, ensuring model consistency—the ability to maintain data consistency between a model or view describing that data. Once implemented, the digital thread is expected to enhance the effectiveness and efficiency of the system development and procurement processes [6]. Developments in improved sensing and monitoring technologies, the seamless transmission of digital data, and advancements in data analytics and trend analysis have the potential to enable manufacturers to save USD 30 billion annually and offer investment return opportunities of nearly USD 8 billion per year through efficient information communication [7]. Additionally, the software development and maintenance costs of the digital thread are estimated to be around USD 8 billion to USD 180 billion, whereas the development and maintenance costs for digital twins may range between USD 1 trillion and USD 2 trillion [8]. Hence, the challenges associated with the digital thread are somewhat smaller, both technically and financially, compared to the concept of digital twins. A survey of researchers and engineers involved in implementing digital twins in the manufacturing industry revealed that the comprehensive updating of 3D digital models throughout all stages of the product realization process, along with integrating inspection data into CAD systems and maintaining the digital thread throughout the entire product development process, constitutes a primary challenge in bridging the gap between academic and industrial research interests [9].

Currently, there is a significant amount of research in the field of digital twins [10]. However, existing development methods for digital twins lack interoperability across different abstraction levels [11], primarily focusing on individual objects and lacking modeling approaches for the entire lifecycle and multiple objects. This limitation hampers the exploration and utilization of data related to various aspects of products [12]. In contrast, research on the digital thread is less extensive. The primary reason is that implementing a digital thread may involve more technical challenges, including data integration, information fluency, and comprehensive lifecycle management. Therefore, there is an urgent need to delineate the key technologies required for the implementation of the digital thread, facilitating the complete connection and integration of information throughout the entire product lifecycle [13].

The remaining sections of this paper are organized as follows: Section 2 outlines the methodology employed for the literature review analysis. Section 3 provides an introduction to the definition of the digital thread and its relationship with other related terms.

Section 4 analyzes the key technologies involved in the construction and implementation of the digital thread. Section 5 presents the current applications of the digital thread. Section 6 delves into the future development of the digital thread and the enabling technologies required. Finally, in Section 7, the paper concludes with a summary of its key findings.

2. Scientometric Analysis

This section aims to comprehensively understand the current status and trends in the field of digital thread research through scientometric analysis. Through a literature review and data statistics, we will unveil the research focuses and development trends of the digital thread in different countries, fields, and applications, providing an in-depth background and reference for the specific discussions on the digital thread in the subsequent sections.

2.1. Literature Review Methodology

The literature review methodology comprises two major steps, literature collection and literature screening, as illustrated in Figure 2.

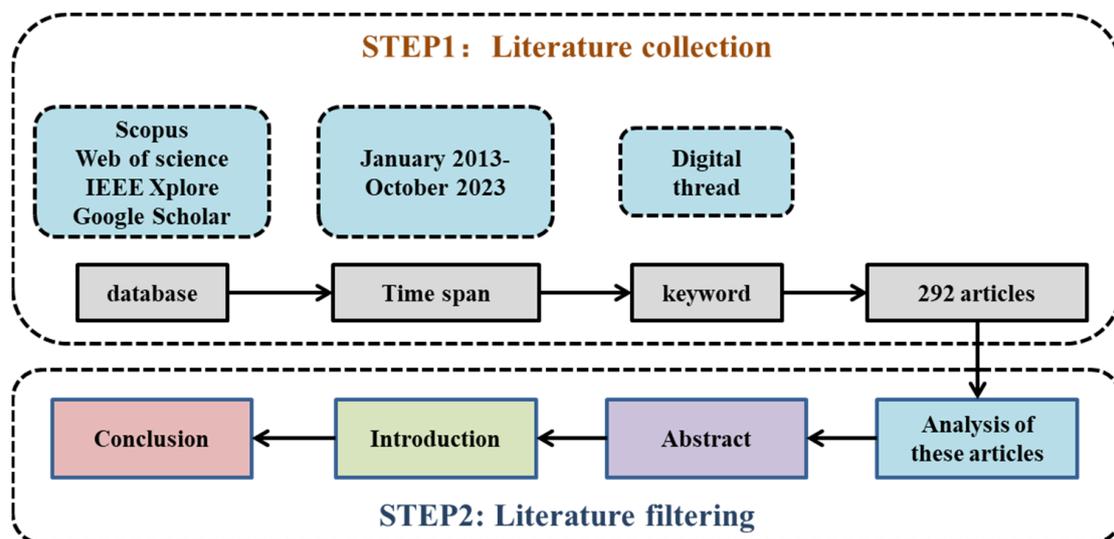


Figure 2. Literature review methodology.

Step 1: Literature collection: As depicted in Figure 1, papers on the digital thread have emerged since 2015. Therefore, the timespan for literature collection spans from January 2015 to 2023. The selected databases include Scopus, the Web of Science, Google Scholar, and IEEE Xplore. Keywords were used to examine whether the term “digital thread” is presented in the titles and abstracts of the retrieved documents. Following the screening process, 292 articles containing the keywords were initially retained.

Step 2: Literature filtering: The filtering process involved reviewing the abstracts, introductions, and conclusions of all selected papers. If any of these sections of a paper contained information related to the definition of the digital thread, its applications, authoritative sources of truth, data linkage, or model integration, the paper was retained for further review; otherwise, it was excluded. Following this process, a final selection of 94 relevant papers was obtained.

2.2. Status Analysis of Digital Thread Research

To illustrate the current state of digital thread development, we conducted a statistical analysis of the publication countries and application domains of the 292 literature items filtered in Step 1, as presented in Figures 3 and 4, respectively.

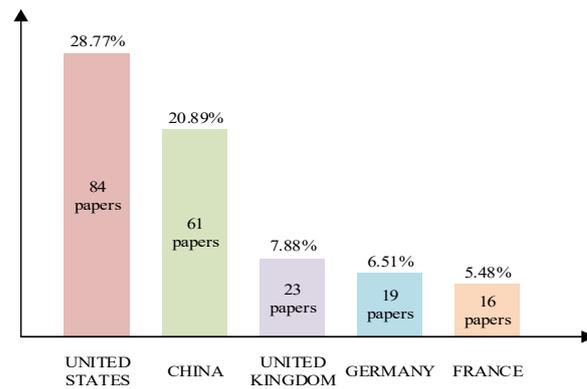


Figure 3. Top five countries and the number of articles.

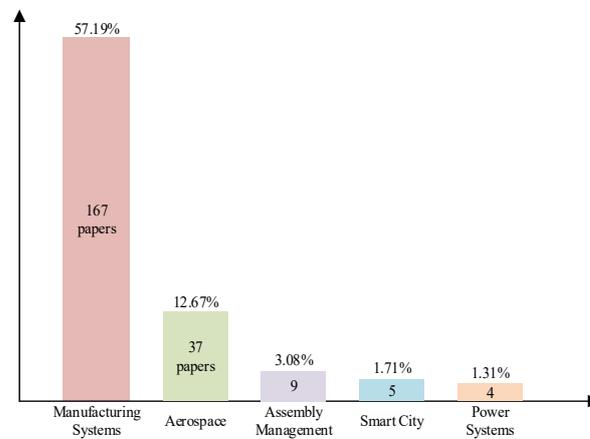


Figure 4. Top five fields and the number of articles.

The top five countries with the highest number of publications on the digital thread are illustrated in Figure 3. The United States, China, the United Kingdom, Germany, and France emerge as the top five countries with the most published papers. Among them, the United States has the highest publication count, accounting for 28.77%. These countries possess advanced technological capabilities and specific information technology infrastructure, fostering a conducive environment for the research, development, and implementation of the digital thread. While the digital thread initially emerged from the United States and China, other countries are showing indications of narrowing the gap in digital thread research.

From an analysis of application domains, the top five fields with the most publications on digital threads are illustrated in Figure 4. The domain of manufacturing systems has the highest publication count, comprising 57.19% of the total. The literature analysis indicates that the current research and application of digital twins are predominantly concentrated in manufacturing sectors, particularly in large-scale defense industries.

3. Definition of the Digital Thread and Related Concepts

While the concept of the digital thread has garnered widespread attention and research interest from both academia and industry in a relatively short period, it lacks a unified definition in terms of its conceptualization and essence. As research and practice in the digital thread continue to advance, diverse definitions have been ascribed to it. Simultaneously, the discourse surrounding the digital thread often intertwines with concepts such as digital twins, Model-Based Systems Engineering (MBSE), and product lifecycle management (PLM). Therefore, this section reviews the definitions of the digital thread, explores its relationships with associated concepts, and introduces a framework for the digital thread based on surrogate models.

3.1. Definitions

In 2013, with substantial support from the DoD, the USAF introduced a novel concept known as the “digital thread”, aiming to extensively leverage digital models to seamlessly integrate physical models and Model-Based Systems Engineering (MBSE) virtual models. The primary motivation behind the inception of this concept was the dynamic reduction of product lifecycle timelines [14]. The US Air Force posited that systems engineering would undergo a transformation from being “document-centric” to “model-centric”, and ultimately to the “digitally surrogate-centric” digital thread [1]. As models continuously update throughout the entire system lifecycle, they remain authoritative representations of the system. Conceptually, the digital thread signifies a merged framework that establishes the conceptual models of the interdisciplinary engineering of various systems’ model elements, pivoting from the traditional focus of MBSE. At the American Institute of Aeronautics and Astronautics (AIAA) Science and Technology Forum in 2015, Walker Kuhn et al. provided a succinct definition of the digital thread: an extensible, configurable, and enterprise-level framework that seamlessly accelerates the authoritative data, information, and knowledge governing interactions, informing decisions throughout the system lifecycle, and delivering the capability to access, integrate, and transform heterogeneous data into actionable information [14].

Additionally, various researchers in the academic community have individually defined the digital thread, and a consolidated overview of these definitions is presented in Table 1. Thomas Hedberg from NIST proposed that the digital thread constitutes an integrated information flow connecting different stages of the product lifecycle. It leverages recognized authoritative data sources like requirements, system architecture, technical data packages (TDP), three-dimensional (3D) CAD models, and project tasks [15]. Dennis J. L. provided a definition for the digital thread as a “communication framework” that allows for an integrated view of data streams and asset data throughout the entire lifecycle, transcending traditional isolated functional perspectives [16]. Singh et al. perceive the digital thread as a model that connects diverse data throughout the product lifecycle, spanning the conceptualization, structural design, testing, manufacturing, service, and disposal stages [17,18]. The digital thread is identified as an integrated information flow using recognized authoritative data sources (e.g., requirements, system architecture, technical data packages (TDP), 3D CAD models) connecting all stages of the product lifecycle [19,20].

Table 1. Digital thread definition.

Publication Time	Originator	Definitions
2013	USAF [3]	refers to a dynamic and real-time assessment of the capabilities possessed by current and future weapon systems throughout the development process.
2015	Kraft [14]	refers to an extensible and configurable enterprise-level framework that, throughout the lifecycle of a system, informs decision-makers by providing the capability to access, integrate, and transform diverse or dispersed data into actionable information.
2016	Thomas Hedberg Jr. [15]	refers to an integrated information flow connecting various stages of the product lifecycle using recognized authoritative data sources.
2018	Dennis J. L. [16]	refers to a “communication framework” that allows for an integrated view of data streams and asset data throughout the entire lifecycle, transcending traditional isolated functional perspectives.
2021	Singh [17,18]	refers to a model that links various data throughout the product lifecycle, encompassing conceptual, structural design, testing, manufacturing, service, and disposal phases.
2022	Vodyaho [21]	refers to an integrated view of all content throughout the entire lifecycle of assets or products, enhancing communication and collaboration.

The objective of the digital thread is to establish an integrated framework that consolidates all stages of the product lifecycle and systems, facilitating efficient and effective lifecycle measurements and supporting a data-driven approach [22]. Specific areas of focus

include knowledge construction, decision support, requirement management, and control. The digital thread is defined as an integrated view of all content throughout the entire lifecycle of assets or products, enhancing communication and collaboration. It can be viewed as an umbrella technology for the development paradigm of modern Large-Scale Complex Systems (LSCDS) [21]. Mies et al. [23] describe the digital thread in the context of additive manufacturing technology. The digital thread facilitates the integration of data into a platform, enabling effortless utilization and access to all data. Wikipedia, based on the relevant literature, provides a definition for the digital thread as “using digital tools and representations for design, assessment, and lifecycle management”. It is a data-driven architecture that connects data collected from all distributed manufacturing systems involved in the product lifecycle, transportation, or any part of the supply chain. The digital thread “is able to collect, transmit, and share data and information between systems throughout the product lifecycle” to achieve real-time decision making, data collection, and product iteration [24].

While these definitions exhibit subtle differences, they share a common theme involving “authoritative data”, “data linkage”, and “model integration”. These three terms are particularly noteworthy as they convey the vision of the digital thread, not solely as a model or a set of models, but aspires to be the definitive repository of authoritative information, encompassing all system knowledge at any given time. To qualify as an authoritative information source, it must be both current and comprehensive. For decision-makers to derive utility from it, someone must organize this information meticulously and promptly, facilitating effective data mining. Further elaboration on this topic is provided in Section 4.

3.2. Related Terms

The digital thread concept shares connections and distinctions with other key terms in the field, notably digital twins, Model-Based Systems Engineering (MBSE), and product lifecycle management (PLM). Exploring these relationships offers insights into how these concepts intertwine and diverge within the domain of digitalized product development and lifecycle management.

3.2.1. The Digital Thread and Digital Twin

Since its inception, the concept of the digital thread has often been closely associated with the notion of the digital twin, considered as a cornerstone and prerequisite for applications involving digital twins. This association is rooted in the digital thread’s facilitation of bidirectional communication between digital twins, contributing to the advancement of digital twin technologies [25]. Zweber et al. delineate the concepts of digital system models, digital twins, and the digital thread by segmenting the product lifecycle into seven components [26,27]. The digital thread collects data from physical entities and updates corresponding digital representations in the virtual space. This connectivity, spanning the system lifecycle, enhances collaboration, changes management, and expedites delivery times for manufacturing and service processes [28]. The definition of a digital twin, as described in [3], entails an integrated multi-physics, multi-scale, probabilistic simulation of a completed system, underpinned by the digital thread. It leverages the most advanced models, sensor data, and input data to replicate and forecast the activities/performance of its physical counterpart across the entire lifecycle. Leveraging the digital thread, digital twins can undergo continuous updates and optimization, leading to improvements in manufacturing processes and product quality [29]. The digital thread links all information generated and stored within the digital twin, allowing seamless flow across various stages of the entire product lifecycle, from inception to disposal [30–32].

The digital thread acts as the foundational infrastructure for the digital twin, integrating data, information, and models from diverse systems across the entire product lifecycle to create a comprehensive view of assets [33]. It provides connectivity across the entire system lifecycle, collecting data from physical twins to update models in the digital twin. Utilizing the digital thread, the digital twin exchanges data between physical and virtual

environments. Furthermore, the digital thread empowers the digital twin to analyze the system's lifecycle, integrate components, and establish connections with external systems within the manufacturing supply chain [34]. In [12], the digital thread is characterized as the interaction of data and information between the physical and virtual domains within the digital twin framework, encompassing the entire product and value lifecycle. It drives the real-time evolution of the digital twin model, facilitating bidirectional data flow through all data channels, as depicted in Figure 5. The digital thread transforms the digital twin system into a closed-loop system, continuously iterating and optimizing through a constant influx of data.

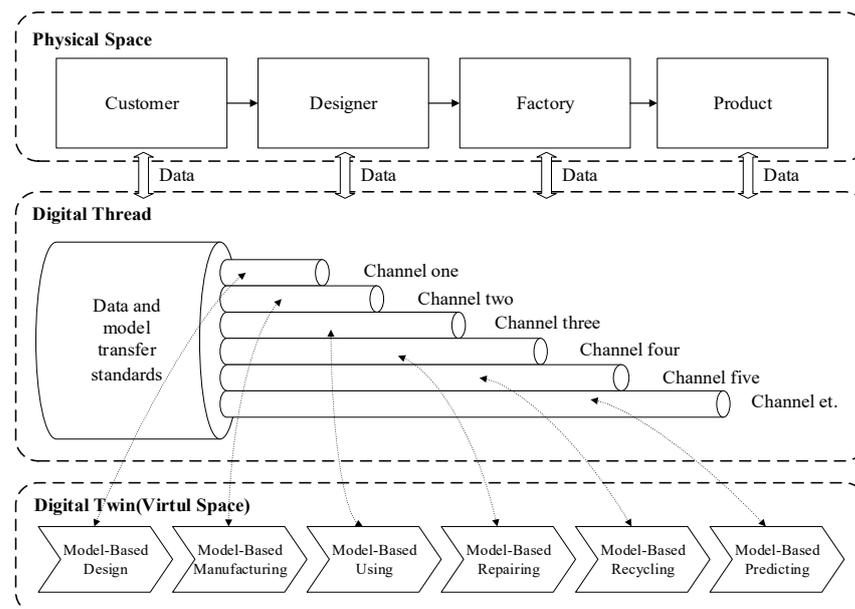


Figure 5. The digital thread facilitates the data and information interaction within the digital twin system [12].

Zhang et al. [35] introduce the development mechanism of the digital thread-based digital twin (DTDT) framework. This framework incorporates a digital thread model that connects system data, designed to segregate and organize data into different threads, such as tool threads, file stream threads, process threads, etc. These threads correspond to various system services, facilitating the management and integration of system data. They also provide interfaces for data access, integration, and transformation between the physical space and the twin space. Liu et al. [36] implement information exchange and collaboration among units through a digital thread-driven approach, enabling them to execute manufacturing tasks and periodically adjust based on the digital twin model. In the context of large-scale personalized manufacturing automation, the digital thread facilitates communication and information transfer among different digital twins. It supports closed-loop feedback, allowing information from one digital twin to better inform the development of a product in another digital twin. The digital thread also promotes knowledge reuse, enabling information generated by one digital twin to be effectively utilized by another [37]. The digital thread is a multi-step process, serving as a complement to the digital twin throughout the entire lifecycle of physical entities. It involves generating the digital twin body and providing all necessary information for updates [32].

3.2.2. The Digital Thread and MBSE

MBSE is a system engineering approach that utilizes models as fundamental tools for designing, analyzing, and documenting systems. System engineers employ modeling languages such as SysML to describe various aspects of the system, including structure, behavior, requirements, and more. Currently, a significant portion of the literature dis-

crossing MBSE applications is confined to the conceptual design phase of systems. Moreover, existing SysML and MBSE methods employ distinct and standalone models for system development [38–40], and manufacturing planning frequently begins in the latter stages of product design, managed by various departments and engineers, resulting in communication gaps, inefficiencies, elevated change costs, and prolonged development cycles. The digital thread endeavors to bridge these silos by furnishing collaborative data and models, providing insights into each silo to enhance product optimization and innovation.

Indeed, MBSE can serve as the inception of the digital thread [41–43]. In [14], the digital thread is proposed as a framework that integrates the concepts of Model-Based Systems Engineering (MBSE) and the top-level architectural models with the physical models generated by discipline engineers during the detailed design phase. A hypothetical scenario is presented to illustrate the application of the digital thread in the development and maintenance of future USAF fighters. Model-Based System-Driven Product Development (SDPD) has been proposed as a framework for crafting pioneering digital manufacturing courses to aid in training the forthcoming cohort of Industry 4.0 engineers [44]. SDPD involves driving product development digitally through integrated models and cross-lifecycle digital threads. The process, propelled by system requirements, establishes traceability for validation objectives.

The digital thread's connectivity, along with the reliable data and knowledge from the digital twin, can expedite the transformation of the systems engineering processes utilized in MBSE [45,46]. With the support of the digital thread, MBSE can better adapt to the digital environment, enhance collaboration between various stages, and improve real-time capabilities and data consistency, making systems engineering more flexible and efficient.

3.2.3. The Digital Thread and PLM

PLM provides a platform for managing data throughout the entire product lifecycle. However, currently, most enterprises utilize it for managing product development data, where engineers engage in activities such as product design, multi-disciplinary collaboration, and supplier coordination based on PLM. The construction of the digital thread involves connecting fragmented and disparate data and information to form a comprehensive view. PLM, as a unified data management and integration platform, supports the integration of various models utilized throughout the development cycle and serves as the backbone for constructing the digital thread [44].

Currently, Siemens AG (Germany Munich) offers the Teamcenter 11.3[®] software, a modern and highly adaptable PLM system that employs the digital thread for manufacturing process innovation. It is a collaborative software establishing the digital thread for creating information throughout the product lifecycle [47].

3.3. Authoritative Surrogate Model for Digital Thread

This study, synthesizing previous definitions of the digital thread and considering its implementation, proposes a novel definition: the digital thread is an extensible and configurable product lifecycle model interconnection line constructed using system modeling languages. It accelerates the seamless and controlled interoperability of enterprise data/information/knowledge, facilitating decision making throughout the entire product lifecycle. The digital thread primarily comprises three components: native models, surrogate models, and relationship sets.

Native models refer to specific models about products, equipment, and business in our manufacturing enterprise. These models are constructed using different modeling/design/analysis tools in various business domains and are generated and utilized by the enterprise business system.

Siedlak et al. [16] proposes the use of surrogate models to reduce the fidelity of native models. Surrogate modeling technology achieves the integration of discipline-specific and typically organization-specific code by building mathematical approximations of the analysis code. Simultaneously, it represents an effective method to reduce the required time

for the integration environment to run. In this study, adaptive improvements are made to the surrogate model.

The surrogate model, in this context, is an abstraction of the native model. It extracts an alternative model composed of elements such as names, attributes, ontology, surrogate function sets, etc. The surrogate model is an abstraction of the native model described in the Unified Modeling Language. It serves as a model for data exchange, facilitating the unification of heterogeneous models and overcoming challenges related to poor interoperability across business domains in native models.

The concepts of native models and surrogate models are introduced, clarifying the relationship between them. By providing a clear definition of the surrogate model, this study advocates the use of surrogate models to replace native models in inter-model interactions.

Based on the defined concept of the digital thread and in conjunction with the theories of MBSE and the surrogate model, a formal expression for the digital thread oriented towards MBSE is formulated. The surrogate model digital thread constitutes a network of surrogate model associations that spans the entire product lifecycle and value chain.

The primary reliance for efficient data flow throughout the entire product lifecycle lies in the surrogate model digital thread. By synthesizing the theories of MBSE and the concept of the surrogate model, a novel definition for the digital thread is proposed. This is formally expressed through a comprehensive language as follows:

$$DT = \{NM, SM, R\} \quad (1)$$

In the equation, NM represents the collection of native models at various stages of the product lifecycle, SM represents the collection of authoritative surrogate models for each native model, and R represents the relationships between native models and surrogate models, domain-specific surrogate models, and cross-domain surrogate models.

The collection of native models (NM) comprises the constitutive elements, interfaces, and representation methods of all native models at various stages of the product lifecycle. Examples include SysML models in the system design phase, 3D models and electronic circuit models in the detailed design phase, Modelica models in the system simulation phase, and Simulink models in the control simulation phase. Native models encompass all the elements that different models aim to express, using various modeling languages and tools for information representation.

Surrogate models (SM) correspond one-to-one with native models, meaning each native model corresponds to a surrogate model. Native models interact through surrogate models, and to ensure the authority and real-time nature of the data in surrogate models, interaction between surrogate models and native models is necessary. This ensures that surrogate models accurately convey the key information of native models. Surrogate models are a scaling down of native models and do not need to express all the information but focus on conveying semantic information.

The relationship set (R) primarily consists of three major types of relationships: the associative relationships between native models and surrogate models, associative relationships among domain-specific surrogate models, and associative relationships among cross-domain surrogate models. The relationships between native models and surrogate models are implemented through model mapping techniques and URI pointers. For instance, detailed design models use surrogate models for semantic expression, where surrogate models store URI pointers for addressing and enabling interaction between native models and surrogate models. Relationships among domain-specific surrogate models are achieved through the language of surrogate models itself, utilizing the analysis of model mapping–constraint relationships and structured methods for expressing relationships. Relationships among cross-domain surrogate models are realized through knowledge graph fusion technology, where each surrogate model can form a subgraph, and relationships between surrogate models are achieved through graph fusion. Visualization management and traceability analysis can be performed based on the knowledge graph.

The evolution of the digital thread is an inevitable trend toward the digitization and integration of the entire lifecycle of complex product development. The initial stages of digital thread development originated with the advancement of model integration techniques, where interactions between models were primarily achieved through defined interfaces. During this phase, manual modifications were often required to facilitate genuine information exchange between models. With the continuous development of Model-Based Definition (MBD) technology, the linkage between design models, particularly three-dimensional product models, and manufacturing processes became closely interconnected. This integration allowed for the utilization and reuse of three-dimensional models across engineering, manufacturing, and maintenance phases. Consequently, it significantly reduced product defects and lowered development costs. The further advancement of digital thread technology benefited from the ongoing application of MBSE. Leveraging MBSE techniques, a seamless digital thread spanning from the system model of the product to detailed design models across various domains was achieved. This model-based, product-lifecycle-oriented digital thread was implemented through system modeling languages, contributing to the overall technological framework tailored for the MBSE-oriented digital thread, as illustrated in Figure 6.

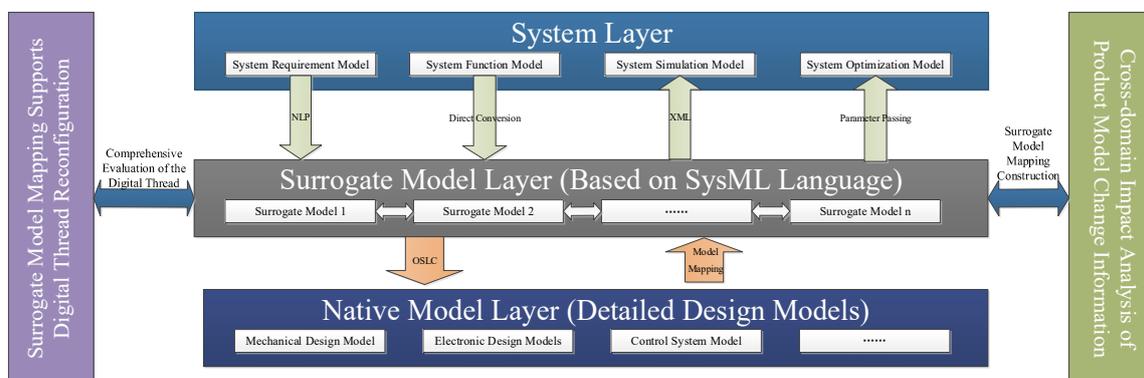


Figure 6. The comprehensive technical framework for MBSE-oriented digital thread.

4. Crucial Technologies of Digital Thread Implementation

In the entire lifecycle of a complex product system, the digital thread facilitates decision making for managers at various levels by providing actionable information derived from disparate data sources. It expedites the interaction between production management data, information, and knowledge, enabling dynamic real-time assessments of a product's capabilities in stages such as capability planning and analysis, preliminary design, detailed design, manufacturing, testing, and maintenance. Through the analysis of the earlier definition of the digital thread, we identify three crucial technologies for its implementation: authoritative sources of truth (ASTs), data linkage, and model integration [48]. The selection of these specific technologies was made due to their fundamental roles in ensuring data accuracy, consistency, and integration throughout the product lifecycle. Unlike some alternative technologies, such as data visualization tools or project management software, ASTs, data linkage, and model integration directly address the challenges of data fragmentation, siloed systems, and disparate models commonly encountered in traditional product development processes. Additionally, we found through the literature review that the majority of discussions surrounding digital thread implementation revolve around these three key technologies. These technologies collectively form the backbone of the digital thread, empowering stakeholders with the ability to make informed decisions based on current and future evaluations of the product.

4.1. Authoritative Sources of Truth

An authoritative source of truth (AST) is a model and database capable of storing standardized modeling and standardized data from all versions throughout the entire lifecycle of a system. It supports the extraction of data and models during the design process, ensuring consistency, traceability, verification, confirmation, visual representation, and automated reporting. This enables a continuous digital representation of the system and full lifecycle traceability, enhancing collaborative efficiency, reducing development time, and improving product quality.

ASTs are not only a core element in the implementation of the digital thread but also a crucial component of the “Digital Engineering Strategy”. According to the “Digital Engineering Strategy”, ASTs are considered the central reference point for models and data throughout the entire lifecycle [49].

In ASTs, “A” signifies uniqueness, holding dominion throughout the system engineering implementation. The data and models within the AST possess commanding influence, exerting impact on other parts of the system, with the rest of the system subservient to the AST. “T” implies precision; thus, the data and models within the AST must be accurate, effective, and unambiguous to ensure both their authority and the correctness of the system engineering implementation. “S” indicates the origin, with the data and models within the authoritative source of truth serving as the wellspring for the design, computation, and analysis processes in the system engineering implementation. These data and models originate from the AST and, in turn, reconverge into the AST during the design and analytical phases.

From this perspective, the digital thread appears more like a meta-model, capable of linking to models in specific disciplines that possess a certain “authoritativeness” [8]. The concept of the AST aims to grant access to the most authoritative data at the element level known in the system design at any given moment [50]. Research in the realm of Industry 4.0 suggests that semantic web technologies may be a key driver for the digital thread [51]. However, a significant portion of current research still employs Model-Based Definition (MBD) as the authoritative source of truth for all product information, replacing traditional 2D drawings [52]. By integrating and hierarchically organizing design information within the MBD model, digital threads are created, providing a common data source for various supportive analyses. Digital threads in MBD can enhance communication, productivity, and the validation of designs. They enable the sharing of data and information across different disciplines within the scope of support, such as reliability, maintainability, testability, safety, and logistics [53].

4.2. Data Linkage

The interoperability of data, systems, and perspectives poses an increasingly severe challenge for industries. The industry necessitates cross-enterprise collaboration, interconnected systems, and correlated data. There are primarily three approaches to achieving interoperability. The first involves standard-based data translation, such as from STEP AP242 to AP238 [33]. The second relies on standards like OSLC and FMI to facilitate interoperability between tools [54]. The third method employs ontologies and knowledge graphs (KGs) for semantic-based data integration [55].

4.2.1. Standard-Based Data Transformation

Lu et al. [56] emphasized the significance of standards in the automation of manufacturing processes within the context of the manufacturing digital thread. As illustrated in Figure 7, the product design initiates from the DOORS requirements model, establishing links with the SysML system model and the PLM model [57]. Subsequently, it connects to the design model in the STEP AP242 format (as-designed model), which is then transformed into the STEP-NC or G-code (as-planned model), encompassing all planning rules and encoding procedures required for the execution of the manufacturing process. All data describing actual construction events in the manufacturing environment are monitored

within MTConnect (as-executed model) [22,58,59]. However, the existing technology falls short of establishing a truly integrated manufacturing thread. There is a pressing need for the development of algorithms and technologies to contextualize and interlink data from multiple standards effectively.

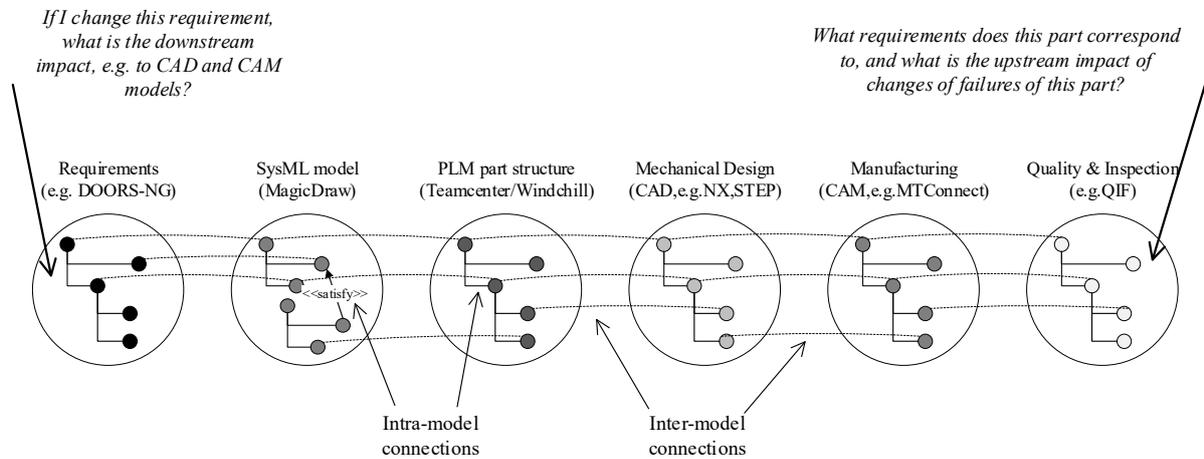


Figure 7. Manufacturing digital thread [22,57–59].

Helu et al. [31] introduced a reference architecture aimed at facilitating the integration of manufacturing and other product lifecycle data within the digital thread. They have also proposed an approach to linking planning and execution data in a standards-based digital thread [33]. Cho et al. [60], aiming to enhance the detection planning strategy for carving surfaces in an improved on-machine measurement system, integrated CAD/CAM data into the CAI process. Another endeavor to integrate CAD, CAM, and CAI involves extracting feature information from STEP files for improved reference data in quality control [61]. Liu et al. [62] encapsulated all information generated during the inspection process into an MBD model. Bonnard et al. [63] introduced a novel STEP-NC data model supporting direct additive manufacturing and hybrid manufacturing from STEP-NC files. It allows the integration of multiple optimization and simulation modules, thereby expanding the possibilities for advanced and intelligent additive manufacturing.

4.2.2. Interface-Based Tool Interoperability

Empirical evidence demonstrates that widespread adoption of interoperability standards for linking various tools can significantly reduce the effort required to connect diverse elements within an extensive IT infrastructure [64]. Therefore, there is a need to construct the digital thread based on industry standards and facilitate connectivity among tools employed in this environment. Standards such as OSLC and FMI have been utilized for both lifecycle and non-lifecycle interoperability, fostering interdisciplinary and correlated interactions [54].

The Open Services for Lifecycle Collaboration (OSLC) offers a universal service definition for information communication, along with a set of general technical protocols and loosely coupled automation techniques (e.g., service discovery, querying, delegated user interfaces, change logs) to support lifecycle collaboration in daily work methods [65]. The OSLC specifications provide a loosely coupled foundation for tool integration within specific domains. The Functional Mock-up Interface (FMI) establishes an open standard for integrating different tools, models, and simulation environments, enabling seamless collaboration among various software and hardware components. This fosters the construction and optimization of digital thread systems [66].

Lu et al. [67] introduced a service-oriented toolchain framework that utilizes the GOPRR meta-meta-modeling approach to construct domain-specific models in the aviation engine domain. Leveraging the OSLC specifications, they established a model-driven digital thread (DT)

platform from a process perspective, enabling collaborative simulation between Functional Model Units (FMUs) and Simulink models. Wu et al. [68] proposed a method for constructing cognitive threads based on the OSLC specification and knowledge graphs. This approach supports decision making and management in Systems of Systems (SoSs).

4.2.3. Semantic Definition-Based Data Integration

The digital thread comprises a variety of lifecycle models and interconnected data through topological relationships. Numerous studies have endeavored to transform existing information models and data, including those based on Extensible Markup Language (XML) and EXPRESS, into ontologies and knowledge graphs. This is because ontology models offer additional formal analysis capabilities and facilitate the reuse of domain knowledge [69]. In recent years, knowledge graphs have emerged as a pivotal technology for linking models and data, with broad applications in constructing and managing the digital thread [70].

Sudarsan et al. [71] advocate using ontologies to expand the proposed product lifecycle management model. Matsokis et al. [72] transform the Semantic Object Model (SOM)-based Unified Modeling Language (UML) into ontologies, showcasing its applicability through a case study in the automotive industry. Orellana [73] outlines the development of a system engineering (SE) reference ontology grounded in ISO/IEC/IEEE 15288 [74]. Unlike other ontologies that target specific systems, this reference ontology centers around system engineering processes, providing context and purpose for establishing and connecting vocabularies across various digital assets.

Panetto et al. [75] developed OntoPDM, aimed at defining product ontologies allowing interoperability using STEP and the International Electrotechnical Commission (IEC) 62264 standards. Barbau et al. [76,77] created OntoSTEP, a tool that facilitates the transformation of STEP schemas and instances into ontologies and knowledge graphs in a simple and automated manner. Sarigecili et al. [78] established EXPRESS data models for tolerance analysis, subsequently using OntoSTEP to convert them into ontologies, facilitating the inference of new knowledge from existing knowledge graphs in a more comprehensible manner. Kwon et al. [55] discussed semantic definition-based data integration using ontologies and knowledge graphs. Ontologies and knowledge graphs offer a structured approach to integrating various data formats and achieving interoperability in data representation. Hedberg et al. [22] introduced an approach utilizing graphical representations to form digital threads, linking and tracking data throughout the entire product lifecycle.

Leveraging semantic-based methods in digital threads has the potential to address challenges related to managing manufacturing data. These approaches provide scalable and contextualized data views, enabling efficient decision making and knowledge generation. The implementation of data integration through ontologies and knowledge graphs remains an ongoing endeavor with ample opportunities. However, the current emphasis is primarily on the early stages of the product lifecycle, posing a hurdle when attempting to establish digital threads.

4.3. Model Integration

The ability to integrate data models from various sources is essential for comprehending, analyzing, and managing product performance [79]. Consequently, numerous frameworks for the digital thread have been proposed, and corresponding platforms have been developed to achieve model integration [30,80–88].

Hedberg et al. [30] introduced the concept of the Lifecycle Information Framework and Technology (LIFT) to support the effective implementation of the digital thread. LIFT represents a conceptual framework that integrates lifecycle information management with emerging and existing technologies, forming the foundational basis for the research agenda on dynamic information modeling. This framework is designed to facilitate digital data management and reuse in manufacturing. It comprises three layers—(1) product lifecycle data, (2) data authentication and traceability, and (3) data-driven applications—as

illustrated in Figure 8. The LIFT concept is committed to linking data across information silos, establishing trust through traceability, and propelling applications with data.

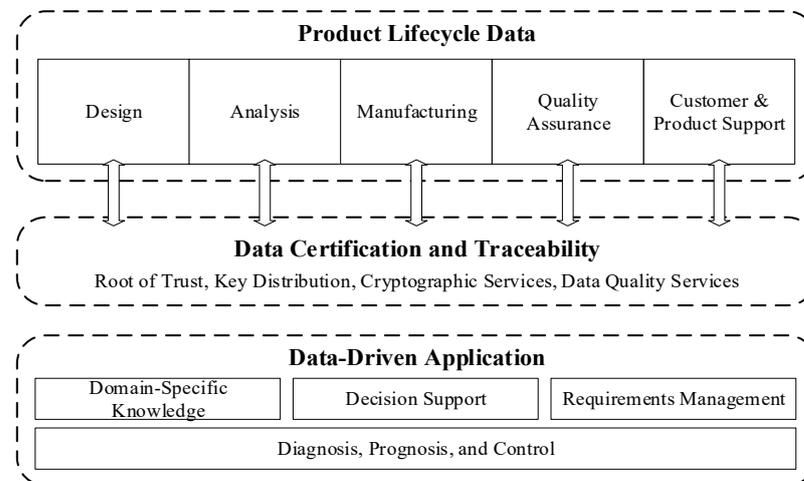


Figure 8. The LIFT architecture [30].

Kovalyov et al. [81] proposed a mathematical framework leveraging category theory to facilitate interoperability across diverse engineering modeling languages and tools for Model-Based Engineering (MBE). This work introduces an approach to address assembly issues that arise during the construction of product models for specific configurations. Airbus Group Innovations (AGI) [82], in pursuit of PLM interoperability, developed the Federated Interoperability Framework (FIF). The FIF integrates open standards from manufacturing, Information Systems (ISs), and Information and Communication Technology (ICT). It sequentially addresses concurrent engineering and collaborative product design in virtual enterprises. However, Tchoffa et al. [83] identified limitations in using semantic graphs to address PLM semantics within the FIF framework. To overcome this challenge, they extended the prior work with a novel approach based on UML2/SysML for composite modeling.

Bajaj et al. [15] introduced a conceptual software environment, the System Lifecycle Handler (SLH), developed for digital thread planning. This environment utilizes the Syndeia platform and demonstrates its functionalities via a web dashboard and standard REST/HTTP API. Nguyen et al. [85] outlined the components of the proposed Flexible, Robust, and Agile Digital Engineering (FADE) platform, including a reference architecture model, a connection matrix, digital use case modeling, a modularized database, and data portability. The FADE platform leverages the digital thread to connect system elements, define interface specifications, and achieve seamless data exchange between digital databases and digital system architecture models. Helu et al. [88] developed an integrated product lifecycle testbed that incorporates design, manufacturing, and inspection technologies. This testbed facilitates shared access and exchange of data and information between CAx and manufacturing labs through networked physical infrastructure.

In addition to academic research, various software companies have developed model integration software to support the implementation of the digital thread. Examples include ModelCenter, TeamCenter, ThingWorx, 3DEXperience, Aras Innovator[®], and Autodesk Fusion Lifecycle. These tools are utilized to manage centralized data storage and integrate simulation models for optimizing product and system design [89].

The digital thread provides significant quantitative and qualitative added values and contributions across various stages of system development, including system design, generating system concepts, system manufacturing, system testing and evaluation, and system support. The digital thread, through the application of real-time data and simulation technology, effectively reduces design risks and costs during the system design phase while promoting collaboration and information sharing among teams, thereby accelerating the

design process and enhancing design quality. During the generation of system concepts, the digital thread rapidly evaluates various design schemes, expediting concept validation and prototype development processes. It also provides a unified platform for teams, facilitating the exploration and discussion of potential solutions and driving innovation. In the system manufacturing phase, the digital thread optimizes production processes and resource utilization through real-time monitoring and data analysis, resulting in increased production efficiency and quality assurance. Additionally, it offers a unified information environment for manufacturing teams to better understand and execute design intent, reducing misunderstandings and errors in the manufacturing process. During the system testing and evaluation phase, the digital thread provides comprehensive data support, enabling a more thorough and traceable testing process. It also fosters communication and collaboration between testing teams and other departments, expediting issue resolution and the implementation of improvements. Finally, in the system support phase, the digital thread achieves real-time monitoring and predictive maintenance, reducing system failure rates and maintenance costs. It provides an integrated information platform for support teams to respond to and resolve user needs and issues more quickly, thereby enhancing customer satisfaction and service quality.

5. Digital Thread Application Scenarios

The concept of the digital thread was initially introduced in the development and manufacturing processes of aircraft. Consequently, its primary applications have been concentrated within industrial giants such as Lockheed Martin, Northrop Grumman, Airbus, and Boeing. However, as the concept and technology of the digital thread have evolved, its application scope has expanded beyond the aviation sector to encompass the entire manufacturing industry, as well as service and commercial sectors. Moreover, some small and medium-sized enterprises (SMEs) have embraced the implementation of the digital thread using cost-effective, low-code software solutions such as the OPC UA protocol, 3DEXperience, Modelica, Node-RED, and MySQL [90].

5.1. Digital Thread in Manufacturing

Lockheed Martin has implemented the digital thread through modern 3D solid design, as well as the application of Design for Manufacture and Assembly (DFMA) tools. This implementation has facilitated collaboration, especially concerning producibility. Assembly and process simulation models contribute to early issue resolution, offering streamlined assembly sequences, visual graphics, and data integrated into electronic instructions [91]. Additionally, a technology known as the Aircraft Digital Twin (ADT) has been proposed [92]. In the context of the ADT, the digital thread is utilized for developing and updating tail number-specific digital twin aircraft models. These models are instrumental in ensuring continuous airworthiness and achieving condition-based maintenance.

Additionally, there is a significant body of research on the application of the digital thread in the field of additive manufacturing [23,93–100]. Deborah provides a comprehensive review of the implementation of the digital thread in additive manufacturing [23]. As depicted in Figure 9, the work by [94] discusses an end-to-end digital thread in additive manufacturing, categorizing it into eight stages: part geometry/design, raw tessellated data, tessellated 3D model, build file (e.g., a “process plan” including the build orientation and process parameters), machine data, part (incorporating geometry with final build parameters and information from in situ measurements), finished part (e.g., part information including any post-processing), and validated part. Through the transformation of information across these eight stages for additive manufacturing components, they establish an additive manufacturing collaborative information system architecture, supporting transparent information exchange, ultimately facilitating quality control throughout the entire lifecycle.

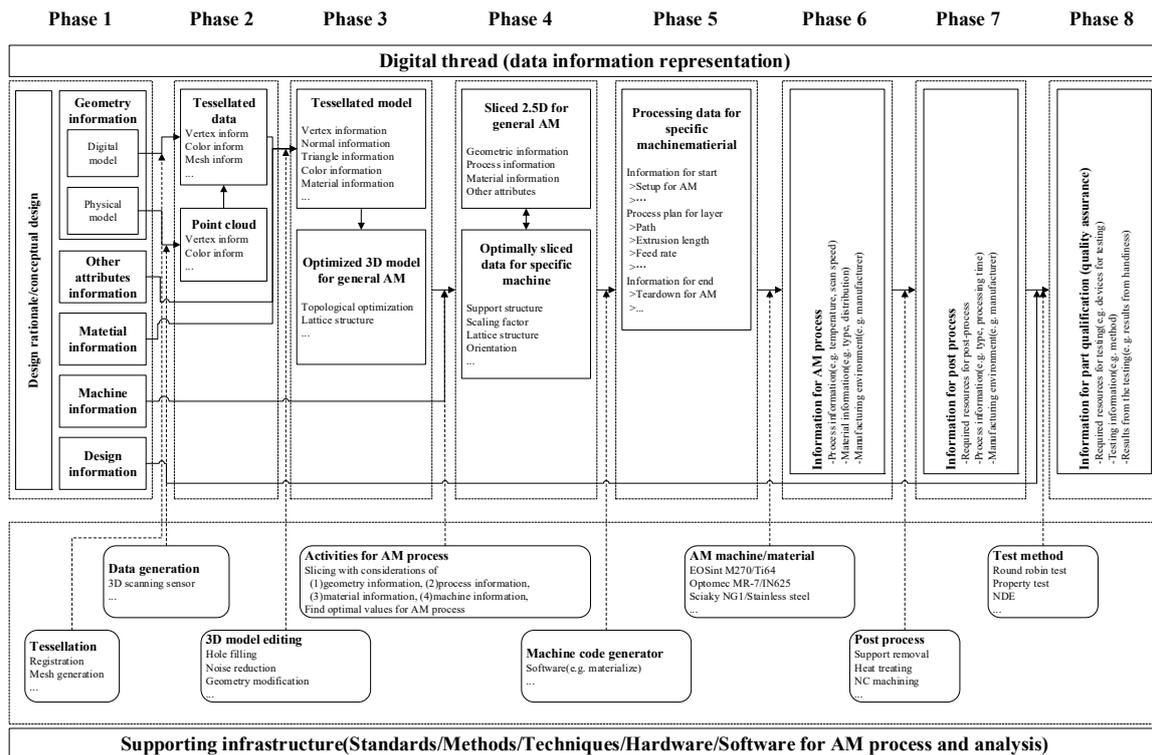


Figure 9. Digital thread in additive manufacturing [94].

The utilization of digital threads and data models enables manageability, traceability, and accountability in additive manufacturing [95]. The Hierarchical Object-Oriented Model (HOOM) serves as a universal data structure for constructing a comprehensive and efficient digital thread for additive manufacturing. It aligns with existing additive manufacturing data standards such as the 3D Manufacturing Format (3MF), the Additive Manufacturing File Format (AMF), the Standard for the Exchange of Product Model Data (STEP), and STEP-compliant Numerical Control (STEP-NC) [96]. The intelligent integration of the additive manufacturing digital thread is crucial in the context of the Fourth Industrial Revolution, as it enhances productivity, improves product quality, facilitates continuous improvement, fosters horizontal integration, and strengthens product traceability [98]. A collaborative effort between the University of Cincinnati and Siemens PLM Software resulted in the development of an additive manufacturing simulation course. This course emphasizes a set of model-based design tools for Powder Bed Fusion Additive Manufacturing (PBFAM) processes, with the objective of actualizing the concept of the “digital thread” through the integration of product design and its manufacturing environment [99].

In the realm of non-destructive evaluation (NDE) systems, NDE data hold valuable information for engineering and management. However, accessing these data is currently challenging due to proprietary interfaces and data formats. The NDE industry needs to address these challenges and embrace standardized interfaces to keep pace with the ongoing industrial revolution. The integration of NDE with the Industrial Internet of Things (IIoT) and digital threads is emphasized as an opportunity for the NDE industry to transition from being a cost center to a value center [101,102].

5.2. Digital Thread in Others

While there is limited research on digital threads in other domains currently, it contributes to the diversified development of digital thread applications. From the above, it is evident that the current applications of digital threads are predominantly concentrated in the manufacturing industry. However, with the advancement of information technology, it can be inferred that digital threads may be applied in various industries such as environ-

mental protection [103], urban transportation [104], etc., as in the digital age, any industry requires authoritative and interoperable data.

The Net Zero Engineering Support Tool (NEST) links various data sources and provides real-time updates and visualizations of information. It integrates data from various sources such as power consumption, emission data, and building information into a centralized data warehouse. The tool processes and analyzes the data to generate insights and predictions. The processed data are then visualized using a graphics library and displayed in the NEST tool. Sensors are installed to monitor the real-time power consumption of buildings, enabling a data-driven approach to achieve net-zero emissions [103].

6. Discussions

By analyzing the current research status of the definition, key technologies, and applications of the digital thread, some conclusions are drawn, and several discussions are proposed.

6.1. Scope of the Digital Thread Concept

The digital thread and digital twin are distinct technologies, and considering the digital thread as a part of digital twins or vice versa is not comprehensive.

Digital twins are empowered by the digital thread, as all the data used in digital twins for assessment, analysis, updates, etc., such as models and sensor data, are captured from the thread. The digital thread enables the holistic management, correlated integration, analysis, and efficient reuse of diverse data, models, and knowledge throughout the entire lifecycle of complex products. It establishes a seamless information channel for complex products, covering processes from design to manufacturing, assembly, inspection, delivery, usage, and maintenance. The emphasis of digital twins lies in abstracting and formalizing models of physical entities, evolving in coordination with the physical entities through data inputs (e.g., sensor data). This ensures consistent coordination with the physical entity throughout its lifecycle. On the other hand, the digital thread not only connects digital twins across different stages but also encompasses information throughout the product's lifecycle, ensuring the consistency of various product information in the event of changes.

Therefore, the digital thread is not a specific product or software but rather an interoperability concept. Various domains can adopt this concept or philosophy to implement the digital thread to varying degrees from different perspectives.

6.2. Analysis on Possible Implementation of Digital Thread in Projects

As part of digital engineering, conducting a general analysis of the potential implementation of the digital thread in projects is crucial. This analysis aims to ensure the effective implementation and application of the digital thread, maximizing project efficiency, quality, and innovation potential.

- (1) Requirement analysis is the first step of the analysis. There is a need to gain a deep understanding of the project's objectives and requirements, including its business goals, technical requirements, expected outcomes, and constraints. Through communication and collaboration with stakeholders, the project's scope, timeline, and budget constraints can be clarified, providing clear guidance for the implementation of the digital thread.
- (2) Technical assessment is paramount. It is necessary to assess the available digital thread technologies and tools to determine which ones are most suitable for the project's needs. This may involve evaluating and comparing technologies such as data management systems, simulation and modeling tools, and collaboration platforms. By evaluating different technology solutions, the most suitable one can be selected for the project's needs, providing guidance for the subsequent implementation process.
- (3) Process analysis is another crucial aspect of implementing the digital thread. It involves reviewing and analyzing the current engineering and business processes of the project to identify integration points and key nodes for the digital thread. This

helps us to understand bottlenecks and challenges in project processes and determine how to optimize these processes through the digital thread, ultimately improving work efficiency, reducing costs, and enhancing product quality.

- (4) Resource assessment is also indispensable. It involves evaluating the human, technical, and financial resources required for the project to ensure the feasibility and cost-effectiveness of implementing the digital thread. This includes assessing team skills and knowledge levels, determining the need for additional training and support, and evaluating the costs and risks involved in the implementation process.
- (5) Risk analysis is an essential part of the analysis. It involves identifying potential risks and challenges and developing corresponding risk management strategies. This may involve assessing risks such as data security, system integration, and technological compatibility to ensure timely responses to potential issues and minimize the impact of risks on the project.
- (6) Monitoring and evaluation are critical aspects of the digital thread implementation process. It is necessary to establish monitoring and evaluation mechanisms to track the progress and effectiveness of digital thread implementation regularly and make timely adjustments and optimizations. This helps to identify and resolve issues promptly, ensure the smooth implementation of the digital thread, and maximize the project's potential for success. Through continuous monitoring and evaluation, the project can proceed smoothly as planned and respond to challenges and changes in a timely manner.

For a company to implement the digital thread, it must cultivate relevant engineers. Therefore, it is particularly important to provide training and educational programs for engineers on the use and implementation of the digital thread.

Engineers require comprehensive training and educational programs to effectively understand and implement the digital thread in their projects. Training programs should cover the foundational concepts of the digital thread. Engineers need to understand the definition, principles, and significance of the digital thread, along with its advantages and differences compared to traditional methods. This foundational understanding sets the stage for further learning and application. Engineers should learn how to use digital tools and software relevant to digital thread implementation, such as data management systems, simulation and modeling tools, and collaboration platforms. Hands-on experience with these tools ensures that engineers are proficient in applying them effectively in real-world projects. Analyzing case studies allows engineers to understand digital thread applications in various industries and project contexts. By examining successful implementations and addressing challenges faced in real projects, engineers can gain valuable insights and practical knowledge applicable to their own projects. Engaging in practical projects allows engineers to apply digital thread concepts and methodologies in simulated or real project scenarios. Through hands-on experience, engineers can develop problem-solving skills and gain confidence in implementing digital thread practices in their projects.

6.3. Enabling Lifecycle Lightweight Interaction through Surrogate Models

The key to the implementation of the digital thread lies in the authoritative source of truth, providing engineers with an effective means of managing the complexity of a product throughout its entire lifecycle by offering a single, reliable data source. However, existing research has predominantly focused on achieving data transformation through tools or integrating models through interfaces, which may not be the optimal approach for realizing the digital thread at present. Leveraging proxy models for digital thread implementation can better facilitate lightweight interaction across the entire product lifecycle. Establishing surrogate models for each phase based on the SysML language allows products to interact within these surrogate models, thereby reducing the amount of data exchanged during model interactions. Moreover, by establishing mapping relationships between surrogate models and native models, traceability of data can be achieved. The use of a system modeling language facilitates the seamless integration of models. In summary, adopting surrogate

models as the foundation for the digital thread, incorporating end-to-end connections of modeling data, simulation data, and collaborative data, achieves lightweight, high-value information continuity. This approach opens up greater possibilities for enhancing digital communication across business domains and fostering innovation.

6.4. Integration of the Digital Thread with Other Technologies

6.4.1. Integration of the Digital Thread with Artificial Intelligence

Artificial intelligence leverages the computational capabilities of computers and machines to emulate human cognition, enabling problem solving and decision making. Supporting technologies for artificial intelligence include big data analytics, decision making, and natural language processing. The potential applications of big data analytics in analyzing the digital thread to enhance manufacturing processes and reduce costs are discussed in [105]. Through natural language processing techniques, textual data can be processed and understood, transforming them into system models while ensuring the accuracy, consistency, and completeness of the models. In conclusion, the integration of the digital thread with artificial intelligence technologies can actualize the vision of cognitive decision making, intelligent data integration, and visualization in the development of smart systems [106].

6.4.2. Blockchain-Based Digital Thread for Ensuring Security

Implementation of the digital thread necessitates multi-stakeholder involvement, thereby subjecting manufacturers and their customers to increased threats [107], such as cybersecurity issues [88]. Blockchain, with its unique attributes, presents a solution for the current limitations of the digital thread and the forthcoming complete digital thread.

The immutability feature of the blockchain ledger can significantly enhance the necessity of provenance, particularly in precision-intensive industries like aerospace, particularly in defense aerospace. This immutability, coupled with cloud-based data management and access control structures, can bolster the digital Thread's capacity to utilize data for faster certification cycles in innovating products, materials, and manufacturing processes [108]. The decentralized architecture of blockchain addresses security and privacy concerns during the adoption of the digital thread [109]. Adhikari et al. [110] proposed a hybrid information architecture to securely manage manufacturing data in the Industry 4.0 era, combining cloud storage and blockchain for the extensive sharing of data requiring integrity and availability. This ensures the security and confidentiality of the digital thread within the context of manufacturing data management.

6.4.3. Cloud Manufacturing (5/6G)-Based Digital Thread

Cloud Manufacturing provides robust support for the implementation of the digital thread, with the advent of the 5G/6G era offering substantial technological backing for handling large-scale data in digital thread implementation.

Adhikari et al. [109] developed a Cloud Manufacturing-as-a-Service (CmaaS) platform, allowing remote clients to extensively customize and manufacture products through cloud-centric communication. They achieved this by designing middleware based on multi-threaded servers and interacting with existing or legacy software platforms, realizing potent decentralized Cloud Manufacturing capabilities. The cloud-based middleware was effectively integrated into hardware assets or manufacturing nodes and interacted seamlessly with them. Yang et al. [111] proposed an active and reactive service combination (PRSC) method for Cloud Manufacturing (CMfg) based on the digital thread. They established a digital thread-driven information interaction architecture, designed PRSC processes, and constituted the digital thread to achieve near-real-time information interaction between enterprises across regions and dynamic changes. Bharadwaj et al. [112] developed a large and continually evolving CAD model repository named "FabWave". Recognizing the significance of capturing and accessing various forms of data generated throughout the product lifecycle, including failed designs, unstructured data, and data from product and

prototype design, as well as the manufacturing process, FabWave advances data-driven approaches to product design and manufacturing.

Furthermore, emerging technologies such as AR/VR have expanded the applications of the digital thread to varying extents [113,114].

7. Conclusions

The digital thread is currently in a rapid development phase, with continuous emerging research and increasingly in-depth studies on the key technologies involved in its implementation. This study reviews 94 papers on the concept, key technologies, and application areas of the digital thread from 2013 to 2023, offering several observational insights. The main contributions of this article are as follows:

- (1) **Conceptual Clarification:** By summarizing different definitions of the digital thread, the conceptual scope is clarified. The relationship between the digital thread and related terms is analyzed, introducing the definition of the surrogate model digital thread.
- (2) **Key Technologies Overview:** A review of crucial technologies in digital thread implementation is provided. The central importance of authoritative data sources is emphasized. The types and methods of data connections between models are summarized, along with the presentation of a model integration framework and platform.
- (3) **Application Summary:** An overview of digital thread applications is presented, with a focus on the current status in areas such as additive manufacturing and non-destructive testing. The article explores the potential applications of the digital thread in emerging fields, promoting its widespread use.

In conclusion, while the digital thread is frequently mentioned, research in this area is still in the early stages of rapid development. A clear review of the literature reveals that, due to the diverse models required to support the product lifecycle in digital thread implementation, researchers have developed various digital thread tools for different stages based on commercial or open-source software tools. This indicates a lack of industry consensus in current digital thread research, and systematic studies face challenges. Therefore, there is an urgent need, facilitated by key technologies like MBSE, to establish a multidisciplinary digital thread universal software platform that spans the entire product lifecycle.

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